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**PROTON EXCHANGE MEMBRANE (PEM)**  
**ELECTROCHEMICAL CELL HAVING AN INTEGRAL,**  
**ELECTRICALLY-CONDUCTIVE, COMPRESSION PAD**

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**BACKGROUND OF THE INVENTION**

The present invention relates generally to proton exchange membrane (PEM) electrochemical cells and relates more particularly to a novel PEM electrochemical cell and to a novel PEM electrochemical cell stack.

In certain controlled environments, such as those found in airplanes, submarines and space crafts, it is often necessary for oxygen to be furnished in order to provide a habitable environment. An electrolysis cell, which uses electricity to convert water to hydrogen and oxygen, represents one type of device capable of producing quantities of oxygen. One common type of electrolysis cell comprises a proton exchange membrane, an anode positioned along one face of the proton exchange membrane, and a cathode positioned along the other face of the proton exchange membrane. To enhance electrolysis, a catalyst, such as platinum, is typically present both at the interface between the anode and the proton exchange membrane and at the interface between the cathode and the proton exchange membrane. The above-described combination of a proton exchange membrane, an anode, a cathode and associated catalysts is commonly referred to in the art as a membrane electrode assembly.

In use, water is delivered to the anode and an electric potential is applied across the two electrodes, thereby causing the electrolyzed water molecules to be converted into protons, electrons and oxygen atoms. The protons migrate through the proton exchange membrane and are reduced at the cathode to form molecular hydrogen. The oxygen atoms do not traverse the proton exchange membrane and, instead, form molecular oxygen at the anode. (An electrolysis cell, when operated

in reverse to generate water and electricity using molecular hydrogen and molecular oxygen as starting materials, is referred to in the art as a fuel cell. Electrolysis cells and fuel cells both constitute electrochemical cells, and all discussion herein pertaining to electrolysis cells is correspondingly applicable to fuel cells.)

Often, a number of electrolysis cells are assembled together in order to meet hydrogen or oxygen production requirements. One common type of assembly is a stack comprising a plurality of stacked electrolysis cells that are electrically connected in series in a bipolar configuration. In a typical stack, each cell includes, in addition to a membrane electrode assembly of the type described above, a pair of multi-layer metal screens, one of said screens being in contact with the outer face of the anode and the other of said screens being in contact with the outer face of the cathode. The screens are used to form the fluid cavities within a cell for the water, hydrogen and oxygen. Each cell additionally includes a pair of polysulfone cell frames, each cell frame peripherally surrounding a screen. The frames are used to peripherally contain the fluids and to conduct the fluids into and out of the screen cavities. Each cell further includes a pair of metal foil separators, one of said separators being positioned against the outer face of the anode screen and the other of said separators being positioned against the outer face of the cathode screen. The separators serve to axially contain the fluids on the active areas of the cell assembly. In addition, the separators and screens together serve to conduct electricity from the anode of one cell to the cathode of its adjacent cell. Plastic gaskets seal the outer faces of the cell frames to the metal separators, the inner faces of the cell frames being sealed to the proton exchange membrane. The cells of the stack are typically compressed between a spring-loaded rigid top end plate and a bottom base plate.

In another typical electrolysis cell stack design, the multi-layer metal screen on the anode side is omitted, and the separator is provided with a set of molded or machined grooves for defining a fluid cavity.

Patents and publications relating to electrolysis cell stacks include the following, all of which are incorporated herein by reference: U.S. Patent No. 6,057,053, inventor Gibb, issued May 2, 2000; U.S. Patent No. 5,350,496, inventors Smith et al., issued September 27, 1994; U.S. Patent No. 5,316,644, inventors Titterington et al., issued May 31, 1994; U.S. Patent No. 5,009,968, inventors Guthrie et al., issued April 23, 1991; and Coker et al., "Industrial and Government Applications of SPE Fuel Cell and Electrolyzers," presented at The Case Western Symposium on "Membranes and Ionic and Electronic Conducting Polymer," May 17-19, 1982 (Cleveland, Ohio).

In order to ensure optimal conversion of water to hydrogen and oxygen by each electrolysis cell in a stack, there must be uniform current distribution across the active areas of the electrodes of each cell. Such uniform current distribution requires uniform contact pressure over the active areas of the electrodes. However, uniform contact pressure over the active areas is seldom attained solely through design since the dimensions of the various components of a cell typically vary within some specified limits due to the production methods used in their fabrication. In fact, standard electrolysis cells often show compounded component dimensional variations of about 0.007 to about 0.010 inch due to fabrication limitations, with additional dimensional variations of up to about 0.002 inch due to differential thermal expansion during electrolysis cell operation.

One approach to the aforementioned problem of maintaining uniform contact pressure over the entire active areas of the electrodes has been to provide an electrically-conductive compression pad between adjacent cells in a stack. One type of electrically-conductive compression pad that has

received widespread use in the art comprises an elastic disk, said disk being provided with an array of transverse holes and transverse slots. The transverse holes are provided in the disk to allow for lateral expansion during compression of the disk. The transverse slots are provided in the disk so that a plurality of parallel metal strips may be woven from one face of the disk to the opposite face of the disk through the slots.

Other types of electrically-conductive compression pads are disclosed in the following patents, all of which are incorporated herein by reference: U.S. Patent No. 5,466,354, inventors Leonida et al., issued November 14, 1995; U.S. Patent No. 5,366,823, inventors Leonida et al., issued November 22, 1994; and U.S. Patent No. 5,324,565, inventors Leonida et al., issued June 28, 1994.

Compression pads of the type described above comprising an elastic disk having parallel metal strips woven therethrough are generally capable of compensating for dimensional variations of a cell to maintain uniform contact over the active areas of the cell up to pressures of about 500 psi. However, for many military and commercial applications, the present inventors have noted that it is also important that a cell stack be lightweight and inexpensive. As can readily be appreciated, the above-described compression pad, which is physically separate from the individual cells of a stack, adds weight and expense to the stack and is, therefore, not optimal for such applications. Other components of conventional cells, such as the metal screens, also add weight and expense to the stack.

## **SUMMARY OF THE INVENTION**

It is an object of the present invention to provide a novel PEM electrochemical cell.

It is another object of the present invention to provide a PEM electrochemical cell that overcomes at least some of the shortcomings discussed above in connection with existing PEM electrochemical cells.

It is still another object of the present invention to provide a novel PEM electrochemical cell stack.

According to one aspect of the invention, the multi-layer metal screen of a conventional PEM electrochemical cell that is placed in contact with the outer face of the cathode is replaced with an electrically-conductive, spring-like, porous pad. Preferably, said pad is a mat of carbon fibers having a density of about 0.2-0.55 g/cm<sup>3</sup>, more preferably 0.44-0.55 g/cm<sup>3</sup>.

Because the pad of the present invention is spring-like (i.e., compressible), a plurality of pad-containing cells can be arranged in a stack, without requiring that a separate compression pad be interposed between adjacent cells for the purpose of maintaining uniform pressure over the active areas of the electrodes, provided that the differential pressure within the stack does not exceed about 400 psi.

In addition, because said pad does not typically experience the same problem of fretting corrosion experienced by a conventional multi-layer screen, a separator plate of the type conventionally used to prevent fretting corrosion of the multi-layer screen may also be omitted from the cell, thereby reducing the cost and weight of the cell.

According to another aspect of the invention, the aforementioned porous pad and the multi-layer anode screen may be approximately equal in thickness to their corresponding peripheral cell

frames or, alternatively, the multi-layer anode screen may be thinner than its peripheral cell frame, with the porous pad being thicker than its peripheral cell frame. In the case of the latter alternative, the two straight separators used to axially contain the fluid cavities are replaced with two bent separators shaped to conform to the outer faces of the multi-layer screen and the porous pad, respectively. Preferably, the reduction in thickness to the multi-layer screen is approximately equal to the increase in thickness to the porous pad, and the two bent separators are identical in shape. Moreover, because the porous pad of the present invention obviates the need for a separate compression pad between adjacent cells (for pressure differentials up to about 400 psi), one of the two separators between adjacent cells may be omitted.

Additional objects, features, aspects and advantages of the present invention will be set forth, in part, in the description which follows and, in part, will be obvious from the description or may be learned by practice of the invention. In the description, reference is made to the accompanying drawings which form a part thereof and in which is shown by way of illustration specific embodiments for practicing the invention. These embodiments will be described in sufficient detail to enable those skilled in the art to practice the invention, and it is to be understood that other embodiments may be utilized and that structural changes may be made without departing from the scope of the invention. The following detailed description is, therefore, not to be taken in a limiting sense, and the scope of the present invention is best defined by the appended claims.

## BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings, which are hereby incorporated into and constitute a part of this specification, illustrate preferred embodiments of the invention and, together with the description, serve to explain the principles of the invention. In the drawings wherein like reference numerals represent like parts:

Fig. 1 is a schematic section view of a conventional PEM electrochemical cell stack;

Fig. 2 is a front view of the compression pad shown in Fig. 1;

Fig. 3 is a schematic section view of a first embodiment of a PEM electrochemical cell stack constructed according to the teachings of the present invention;

Fig. 4 is a schematic section view of a second embodiment of a PEM electrochemical cell stack constructed according to the teachings of the present invention;

Fig. 5 is a graphic depiction of the spring rate and compression set, as a function of compression pressure, of an individual PEM electrochemical cell of the stack of Fig. 3, said individual PEM electrochemical cell comprising a  $0.44 \text{ g/cm}^3$  porous graphite pad having a diameter of 5.6 inches and a nominal thickness of 0.085 inch;

Fig. 6 is a graphic depiction of the spring rate and compression set, as a function of compression pressure, of an individual PEM electrochemical cell of the stack of Fig. 3, said individual PEM electrochemical cell comprising a  $0.48 \text{ g/cm}^3$  porous graphite pad having a diameter of 5.6 inches and a nominal thickness of 0.084;

Fig. 7 is a graphic depiction of the spring rate and compression set, as a function of compression pressure, of an individual PEM electrochemical cell of the stack of Fig. 3, said

individual PEM electrochemical cell comprising a  $0.55 \text{ g/cm}^3$  porous graphite pad having a diameter of 5.6 inches and a nominal thickness of 0.079 inch;

Fig. 8 is a graphic depiction of the electrolyzing performance, as a function of differential pressure, of an individual PEM electrochemical cell comprising a  $0.55 \text{ g/cm}^3$  porous graphite pad having a thickness of 0.08 inch and a diameter of 1.25 inch; and

Fig. 9 is a graphic depiction of the electrolyzing performance, as a function of time, of an individual PEM electrochemical cell comprising a  $0.44 \text{ g/cm}^3$  porous graphite pad having a thickness of 0.08 inch and a diameter of 1.25 inch, said cell being operated at a differential pressure of 400 psi.

## **DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS**

Referring now to Fig. 1, there is shown a schematic section view of a conventional PEM electrochemical cell stack, said conventional PEM electrochemical cell stack being represented generally by reference numeral 11.

Stack 11 comprises a pair of PEM electrochemical cells 13-1 and 13-2 arranged in series in a bipolar configuration and a compression pad 15 interposed between cells 13-1 and 13-2 for electrically connecting cells 13-1 and 13-2 and for maintaining uniform contact over the active areas of cells 13-1 and 13-2. Although, for purposes of simplicity and clarity, stack 11 is shown in the present embodiment comprising only two cells 13-1 and 13-2 and a single compression pad 15, it can readily be appreciated that stack 11 may be modified to include as many as one hundred or more cells 13, with each adjacent pair of cells 13 being separated by an interposed compression pad 15.

Each cell 13 includes a proton exchange membrane 17, an anode 19 positioned along one face of proton exchange membrane 17, and a cathode 21 positioned along the other face of proton exchange membrane 17. A platinum film or other suitable catalyst (not shown) is positioned at the interface between anode 19 and proton exchange membrane 17, and a second platinum film or other suitable catalyst (not shown) is positioned at the interface between cathode 21 and proton exchange membrane 17.

Each cell 13 also comprises a pair of multi-layer metal screens 31 and 33. Screen 31 is placed in contact with the outer face of anode 19 and is used to define a fluid cavity through which water may pass and in which molecular oxygen generated at anode 19 may be collected. Screen 33 is placed in contact with the outer face of cathode 21 and is used to define a fluid cavity in which molecular hydrogen generated at cathode 21 may be collected.

Each cell 13 additionally comprises a pair of polysulfone cell frames 35 and 37, cell frame 35 peripherally surrounding screen 31 and cell frame 37 peripherally surrounding screen 33. Frames 35 and 37 are used to peripherally contain the fluids present within screens 31 and 33, respectively, and to conduct the fluids into and out of screens 31 and 33, respectively. Each of frames 35 and 37 typically has a thickness of about 0.060 inch.

Each cell 13 further comprises a pair of separators 41 and 43. Separators 41 and 43 are typically made of a metal foil, such as a titanium foil having a thickness of about 0.001 inch. Separator 41 is positioned against the outer face of screen 31. Separator 43 is positioned against the outer face of an electrically-conductive separator plate 45 which, in turn, is positioned against the outer face of screen 33. (Separator plate 45 prevents screen 33 from experiencing fretting corrosion caused by contact with separator 43.) Separators 41 and 43 serve to axially contain the fluids within screens 31 and 33, respectively. In addition, separators 41 and 43, separator plate 45, and screens 31 and 33 together serve to conduct electricity from anode 19 of cell 13-1 to cathode 21 of cell 13-2.

Each cell 13 also comprises a pair of plastic gaskets 47 and 49, gasket 47 sealing the outer face of frame 35 to separator 41 and gasket 49 sealing the outer face of frame 37 to separator 43. Each of gaskets 47 and 49 typically has a thickness of about 0.005 inch. The inner faces of frames 35 and 37 are sealed to proton exchange membrane 17.

Referring now to Fig. 2, compression pad 15 is shown in greater detail and can be seen to include a spring-like disk 61. Disk 61 is typically made of a silicone rubber and has a thickness of about 0.065 inch. Disk 61 is provided with a patterned array of transverse holes 63 and transverse slots 65. Holes 63 allow for lateral expansion of disk 61 when disk 61 is compressed so that the overall surface area of disk 61 does not increase significantly during compression. Slots 65 are used

to receive a plurality of metal strips 67. Strips 67, which typically have a thickness of about 0.005 inch, are woven in a parallel arrangement from one face of disk 61 to the opposite face of disk 61 through slots 65. Strips 67 are typically provided with transverse breaks 69 to allow for expansion.

Referring back to Fig. 1, pad 15 serves to evenly distribute pressure over the entireties of separators 41 and 43 (and, consequently, over the entire active areas of cells 13-1 and 13-2), provided that the differential pressure in the stack does not exceed about 500 psi. In addition, each strip 67 serves to electrically interconnect separators 41 and 43 at a plurality of points along the length of said strip 67. However, as explained above, the present inventors have noted that compression pad 15 adds weight and expense to stack 11 that, for many military and commercial applications, is undesirable.

Referring now to Fig. 3, there is shown a schematic section view of a first embodiment of a PEM electrochemical cell stack constructed according to the teachings of the present invention, said PEM electrochemical cell stack being represented generally by reference numeral 101.

Stack 101 is similar in certain respects to stack 11. For instance, stack 101 comprises a pair of cells 103-1 and 103-2 arranged in series in a bipolar configuration (it being understood that stack 101 may be modified to include up to one hundred or more cells 103 arranged in series in a bipolar configuration). Each cell 103 comprises a proton exchange membrane 17, an anode 19 positioned along one face of proton exchange membrane 17, and a cathode 21 positioned along the other face of proton exchange membrane 17. A first platinum film or other suitable catalyst (not shown) is positioned at the interface between anode 19 and proton exchange membrane 17, and a second platinum film or other suitable catalyst (not shown) is positioned at the interface between cathode 21 and proton exchange membrane 17. Each cell 103 also comprises a metal screen 31 placed in

contact with the outer face of anode 19, a pair of polysulfone cell frames 35 and 37, and a pair of plastic gaskets 47 and 49.

Stack 101, however, differs notably from stack 11 in that stack 101 does not include screen 33, but rather, in its place comprises an electrically-conductive, compressible (i.e., spring-like), porous pad 105. In the present embodiment, pad 105 is a porous mat of randomly-arranged graphite fibers, said porous mat having a density of about 0.2-0.55 g/cm<sup>3</sup> and a relaxed or decompressed thickness of about 0.08 inch (Spectracarb Corporation, Lawrence, MA). It should be understood, however, that pad 105 may be made of materials other than carbon fibers, provided that the resulting product possesses sufficient porosity, electrical conductivity and compressibility.

Because pad 105 is compressible up to differential pressures of about 400 psi, one advantage of stack 101, as compared to stack 11, is that compression pad 15 may be omitted from stack 101, thereby resulting in a reduction in cost and weight to stack 101. In addition, because pad 105 is unlikely to experience fretting corrosion, separator plate 45 may also be omitted from stack 101, thereby resulting in a further reduction in cost and weight to stack 101. Moreover, pad 105, itself, is typically lighter and cheaper than multi-layer metal screen 31, which is typically made of zirconium and which requires the welding together of its component layers. (In addition, platinum plating is also often applied to screen 31 to minimize contact resistance.) Furthermore, unlike metal screen 31, pad 105 is unlikely to become embrittled due to prolonged exposure to hydrogen gas. Lastly, pad 105 may be impregnated with polymeric or elastomeric materials, such as Teflon, Kynar, fluoroelastomers, ionomers (e.g., Nafion), to enhance its structural integrity and spring rate, without sacrificing other essential properties, such as high conductivity and porosity.

Stack 101 further differs from stack 11 in that stack 101 includes a pair of straight metal foil separators 111-1 and 111-2, instead of a straight separator 41 and a bent separator 43, separator 43 being bent to accommodate compression pad 15.

Referring now to Fig. 4, there is shown a schematic section view of a second embodiment of a PEM electrochemical cell stack constructed according to the teachings of the present invention, said PEM electrochemical cell stack being represented generally by reference numeral 201.

Stack 201 is similar in many respects to stack 101, the principal differences between the two stacks being that (i) pad 105 of stack 101 is replaced with a pad 203 in stack 201, pad 203 being identical to pad 105, except that pad 203 has an increased relaxed or decompressed thickness of about 0.11 inch (and a compressed thickness of about 0.095 inch); (ii) screen 31 of stack 101 is replaced with a screen 205 in stack 201, screen 205 being similar to screen 31 but having fewer layers and having a reduced thickness of about 0.035 inch (as compared to a thickness of about 0.060 inch for screen 31); and (iii) separators 111-1 and 111-2 of stack 101 are with replaced with a single separator 207, separator 207 being positioned between a pair of adjacent cells 204-1 and 204-2 and having a bent shape (i.e., hat-shaped) to conform to the outer face of screen 205 for cell 204-2 and the outer face of pad 203 (as well as a portion of the top and bottom of pad 203) for cell 204-1.

The following examples are provided for illustrative purposes only and are in no way intended to limit the scope of the present invention:

#### EXAMPLE 1

Three different compression pads 105 having respective densities of 0.44 g/cm<sup>3</sup>, 0.48 g/cm<sup>3</sup> and 0.55 g/cm<sup>3</sup>, respective thicknesses of 0.085 inch, 0.084 inch and 0.079 inch, and each having a diameter of 5.6 inches were tested for both spring rate and compression set by incorporation into

three corresponding individual cells 103. The results of said testing are graphically depicted in Figs. 5 through 7, respectively. As can be seen, the most desirable pad 105 of the three tested was the pad having a density of  $0.55 \text{ g/cm}^3$  since it resulted in the most modest range of deflection in the pressure range of interest (200 to 500 psi), with negligible compression set or structural degradation.

#### EXAMPLE 2

The electrolyzing performance of a cell 103 comprising a pad 105 having a density of  $0.55 \text{ g/cm}^3$  and a diameter of 1.25 inch was tested as a function of the differential between the hydrogen pressure and the oxygen pressure (oxygen being generated at ambient pressure). The results are shown in Fig. 8. As can be seen, there was essentially no change in performance for differential pressures up to 400 psi, indicating good spring rate and no compression set. It is believed that Teflon impregnation of the pad would further enhance structural integrity and spring rate, without sacrificing other essential properties.

#### EXAMPLE 3

The electrolyzing stability of a cell 103 comprising a pad 105 having a density of  $0.44 \text{ g/cm}^3$  and a diameter of 1.25 inch was tested over a 12 hour period at a differential pressure of 400 psi. The results are shown in Fig. 9. As can be seen, the cell 103 remained very stable over the entire period in question.

The embodiments of the present invention recited herein are intended to be merely exemplary and those skilled in the art will be able to make numerous variations and modifications to it without departing from the spirit of the present invention. All such variations and modifications are intended to be within the scope of the present invention as defined by the claims appended hereto.